Driving Performance After an Extended Period of Travel in an Automated Highway System

NOTE TO READER:

THIS IS A LARGE DOCUMENT

Due to its large size, this document has been segmented into multiple files. All files separate from this main document file are accessible from links (blue type) in the table of contents or the body of the document.

Driving Performance After an Extended Period of Travel in an Automated Highway System

PUBLICATION NO. FHWA-RD-98-051 APRIL 1998

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report presents the results of one of a series of experiments that investigated driver performance in a generic Automated Highway System configuration. The experimental research was conducted in an advanced driving simulator and investigated the effects on normal driving of traveling under automated control for about 30 min. Traveling under automated control did not have an adverse effect on lane keeping and speed control. But, the minimum following distance and the minimum size of gaps rejected in lane incursions (incomplete lane changes) may have decreased as the result of automated travel. This report will be of interest to engineers and researchers involved in Intelligent Transportation Systems and other advanced highway systems.

Sufficient copies of the report are being distributed to provide a minimum of two copies to each FHWA regional and division office, and five copies to each State highway agency. Direct distribution is being made to division offices.

A. George Ostensen, Director
Office of Safety and Traffic Operations
Research and Development

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-98-051	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle DRIVING PERFORMANCE AFTER AN EXTENDED PERIOD OF TRAVEL IN AN AUTOMATED HIGHWAY SYSTEM	5. Report Date April 1998 6. Performing Organization Code .
7. Author(s) A. John R. Bloomfield B. Lee Levitan A. Angela R. Grant A. Timothy L. Brown A. Jon M. Hankey	8. Performing Organization Report No. 10. Work Unit No. (TRAIS) 3B4d1012
9. Performing Organization Name and Address A. The University of Iowa Center for Computer Aided Design 208 Engineering Research Facility Iowa City, Iowa 52242 B. Honeywell Inc. 3660 Technology Drive Minneapolis, MN 55418	11. Contract or Grant No. DTFH61-92-C-00100 13. Type of Report and Period Covered Final Working Paper 10/95 through 3/97
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296	14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR)-Elizabeth Alicandri, HSR-30

16. Abstract
The objective of this experiment—part of a series exploring human factors issues related to the Automated Highway System (AHS)—was to determine whether driving performance would be affected by extended travel under automated control at a velocity higher than the speed limit and closer to the vehicles ahead than usual. The experiment, conducted in the Iowa Driving Simulator, used a generic AHS configuration in which the left lane was reserved for automated vehicles. Unautomated vehicles traveled in the center and right lanes, the center lane was not a dedicated transition lane, and there were no barriers between the automated and unautomated lanes. Forty-eight drivers participated in the experiment—half were male, half were female; half were between the ages of 25 and 34 years, half aged 65 or older. Lane-keeping, speed control, following distance, lane-change, and incursion measures were used to compare driving performance before and after the drivers had traveled under automated control.

Results. (1) While it is not clear whether the experience of traveling under automated control produced the reductions in steering instability and velocity instability and the increased number of velocity fluctuations—all of which can be considered as improvements in driving performance—that were found for the drivers in the experimental group in the late data-collection period (since similar improvements were found for the drivers in the control group), it is clear that the experience of traveling under automated control did not have an adverse affect on lane keeping and speed control. (2) The minimum following distance and the minimum size of the rejected incursion gaps may have decreased for the drivers who traveled under automated control for an extended period of time, and they spent more time in the center lane both before and after they traveled under automated control. (3) The drivers who traveled under automated control expressed a preference for larger intra-string gaps than those that they experienced in this experiment. The drivers who were given control of both steering and speed simultaneously gave a significantly stronger positive response, when asked how they felt about the method of control transfer they used, than the drivers who first had to control speed, and then subsequently steering. (4) The smallest gaps for lane changes and incursions were similar—suggesting the minimum gap acceptable for a lane change is between 1.6 s and 2.4 s.

17. Key Words Automated highway system, human performance, driving simulation, automated driving, intelligent vehicles, human factors.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 144	22. Price

Form DOT F1700.7 (8-72) Reproduction of Completed Page Authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

NOTE: Volumes greater than 1000 l shall be shown in m^3.

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

Section | Page

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

Table | Page

SECTION 1. INTERDUCTION AND OVERVIEW

INTRODUCTION

Currently, a great deal of attention is being focused on the possibility of using advanced technologies to develop an Automated Highway System (AHS), which would allow hands-ff/feet-off travel in one's own vehicle. Human factors issues related to potential implementation of an AHS are being explored in an ongoing, two-stage program that is being conducted for the Federal Highway Administration (FHWA). In the first stage of the program, seven experiments were conducted using the Iowa Driving Simulator. In the second stage, seven additional experiments were conducted, with the first five of them being run together. This report presents the results of the third, fourth, and fifth experiments of the second stage of the program.

The experiments reported here, like all those conducted in stage I, used an AHS configuration that would require little structural alteration to the roadways. It consists of a three-lane expressway in which the left-most lane is reserved for automated traffic that travels in strings of up to four vehicles, while the vehicles that remain under the control of their drivers travel in the center and right lanes. With this configuration, the center lane is also used by vehicles that are in the process of moving into or out of the automated lane—there is no dedicated transition lane to and from the AHS lane. Also, there are no barriers between the automated and unautomated lanes.

The experiments conducted in stage I of the program investigated the following:

- The transfer of control from the AHS to the driver of the simulator vehicle as the vehicle left the automated lane. (1)

- The transfer of control from the driver to the AHS as the simulator vehicle entered the automated lane. (2,3)

- The acceptability to a driver in the automated lane of decreasing vehicle separations as a vehicle entered the automated lane ahead of the driver. (4)

- The effectiveness of the driver when he/she was required to control the steering and/or speed when traveling through a segment of the expressway in which the capability of the AHS was reduced.(5)

- The effect on normal driving behavior after traveling under automated control for very brief periods of time. (6)

The five of stage II experiments were run together in a single combined experiment. These experiments examined:

- The behavior of the driver during the time that his/her vehicle was traveling under automated control (experiment 1).
- The kind of information that the driver wanted to have available when his/her vehicle was traveling under automated control (experiment 2).
- The effect on normal driving behavior after traveling under automated control for an extended period of time (experiment 3).
- The effect on normal driving behavior when different gap sizes between the driver's vehicle and the vehicle ahead during travel under automated control were used (experiment 4).
- The effect on normal driving behavior when different methods by which control was transferred from the automated system to the driver were used (experiment 5).

The results of the first two experiments are reported elsewhere.(7) The remaining three experiments, which all focus on the effect on normal driving behavior of traveling in an automated highway system, are addressed in this report.

THE EFFECTS OF TRAVELING IN AN AUTOMATED HIGHWAY SYSTEM

Two previous studies in this series of experiments provided some information about the possible carryover effects of traveling under automated control, although in both of those studies the drivers traveled under automated control for only brief periods of time.

In the first of these studies, Bloomfield, Buck, Carroll, Booth, Romano, McGehee, and North investigated the transfer of control from the AHS to the driver when the driver's vehicle was leaving the automated lane.(1) After traveling in the automated lane for 2 to 3 min, each driver resumed control of the simulator vehicle while it was still in the automated lane, traveling at the designated AHS velocity. On taking control, the driver was responsible for moving from the automated lane to the center lane. Bloomfield et al. found that the driver decelerated before moving the vehicle into the center lane, and that the velocity to which the driver decelerated varied as a function of the designated AHS velocity. When the designated AHS velocity was 104.7 km/h (65 mi/h), the driver reduced the speed of the vehicle to 91.5 km/h (56.8 mi/h) before moving from the automated lane to the center lane, i.e., the driver decelerated until the speed of the vehicle approximated the speed limit, which was 88.6 km/h (55 mi/h) in the unautomated lanes. In contrast, when the driver was reducing speed from the higher designated AHS velocities, the driver left the automated lane traveling at speeds that were considerably higher than the speed limit. When the designated AHS velocity was 128.8 km/h (80 mi/h), the driver left the automated lane at 104.4 km/h (64.9 mi/h), and when the designated AHS velocity was 153.0 km/h (95 mi/h) he/she left the automated lane at 109.8 km/h (68.9 mi/h).

The second study (Bloomfield, Christensen, and Carroll) directly investigated the effects on driving performance of brief periods of travel under automated control.[6] However, in this study, the driving-performance data equivalent to those obtained in the early study, i.e., driving-performance data obtained during the period in which the driver was decelerating immediately after leaving the automated lane, were not examined. Instead, the experiment focused on the driver's performance after he/she had achieved a stable cruising speed. Bloomfield, Christensen, and Carroll found that there was no decrement in steering performance after the driver had experienced a relatively limited amount of travel under automated control.[6] They also found that, although there was less velocity drift when the driver was in the center lane after traveling under automated control, there was more velocity instability and there were fewer velocity fluctuations. This means that, in order to maintain a chosen velocity before traveling in the AHS, the driver made more frequent, smaller velocity corrections. In contrast, in order to maintain a velocity after traveling in the AHS, the driver made less frequent, larger velocity corrections.[6] Bloomfield, Christensen, and Carroll suggested that traveling under automated control for an extended period may cause the driver to become less attentive to speed.[6] The current combined experiment explored this possibility.

As in the two earlier experiments, there was one experimental session for each driver in this experiment. However, in this session, there was only one trial. This trial lasted approximately 1 h, and in it the driver traveled in the automated lane for an extended period of time.

When the trial began, the driver's car was positioned on the entry ramp of an expressway. The driver's task was to drive into the right lane of the expressway, move to the center lane, and, when instructed, transfer control of the car to the automated system. On taking control, the AHS drove the simulator vehicle into the automated (left) lane and moved it to the last position in a string of automated vehicles. Then, the vehicle traveled under automated control for at least 35 min. During this period, the first two experiments were conducted: the behavior of the driver was videotaped, and various types of information about the trip and of potential interest to the driver were made available on a laptop computer mounted in the car.

Forty-eight drivers participated in the combined experiment: 36 were in the experimental groups and 12 were in the control group. The three combined experiments reported here investigated the effects on normal driving performance of traveling under automated control, varying the gap between the driver's car and the vehicle ahead, and varying the method by which control was transferred back to the driver. Driving-performance data were obtained in two data-collection periods, the first of which occurred relatively early in the trial, the second of which occurred relatively late. Table 1 shows the timeline for the two groups. For the drivers in both the control and experimental groups, the early data-collection period (which lasted 9.5 min) started after a 5-min practice driving period that began the trial. The late data-collection period lasted 9.0 min and started when drivers in the experimental group regained control of their vehicles after having been under automated control for at least 35 min.

Table 1. Trial timeline.

Length of Time	Experimental-Group Activity	Control-Group Activity
Trial start	Car on expressway entry ramp	Car on expressway entry ramp
9.5 min[a] **Early data-collection period**	Driver drove onto expressway, drove in right and center lanes	Driver drove onto expressway, drove in right and center lanes
About 1 min	AHS took control in center lane and drove car into left lane; car became last in a string	Driver drove in right and center lanes
At least 35 min	Car under automated control	Driver drove in right and center lanes
About 1 min	AHS drove car into center lane and released control to driver	Driver drove in right and center lanes
About 9 min **Late data-collection period**	Driver drove in center and right lanes	Driver drove in right and center lanes

[a] Minutes 0 through 5 were for driver practice; no data were analyzed for that time period.

While the driver's car was in the automated lane, it traveled at a velocity of 104.7 km/h (65 mi/h), i.e., 16.1 km/h (10 mi/h) faster than the speed limit in the unautomated lanes. During this period, the gap between the driver's car and the vehicle immediately ahead in the string of automated vehicles was much smaller than the following distances usually chosen by a driver in normal driving—gap sizes of 0.0625 s and 0.0344 s were used. In addition, three methods of transferring control from the AHS to the driver were investigated: (1) the driver gained control of the speed first and then steering control, (2) the driver gained control of the steering first and then speed, and (3) the driver gained control of the speed and steering simultaneously. Objective driving-performance data were collected during the periods of time that the driver was in control of the vehicle before and after traveling in the AHS. Subsequently, the pre-AHS and post-AHS data of the drivers in the experimental groups were compared with the driving-performance data obtained from the drivers in the control group to examine whether the experience of traveling in an automated lane had an impact on manual driving behavior.

OBJECTIVES OF THIS EXPERIMENT

The objectives of the combined experiments were:

- To determine whether driving behavior would be affected by traveling for an extended period of time under automated control at a speed greater than the speed limit and with a much-shorter-than-usual distance between the driver's car and the vehicle immediately ahead.
- To determine the effect on the driver's post-AHS behavior of varying the distance between the driver's car and the vehicle immediately ahead while the driver was traveling in the automated lane for an extended period of time.
- To determine the effect on the driver's post-AHS behavior of varying the method of transferring control from the AHS back to the driver as his/her vehicle left the automated lane.

To achieve these objectives, driving-performance data were obtained from the drivers in the experimental groups both before and after they traveled under automated control, and from the drivers in the control group in two data-collection periods that occurred early and late in the trial. The analyses of these data focused on the following experimental questions:

- *Does traveling under automated control for an extended period of time have an immediate effect on post-AHS driving performance?*

- *Does traveling under automated control for an extended period of time have a prolonged effect on post-AHS driving performance?*

- *Does the age of the driver affect the driver's performance after he/she has traveled under automated control for an extended period of time?*

- *Does the method of transferring control back to the driver after he/she has traveled in the automated lane for an extended period of time affect post-AHS driving performance?*

- *Does the gap between the vehicle ahead and the driver's vehicle (i.e., intra-string gap), while traveling in the automated lane for an extended period of time, affect post-AHS driving performance?*

SECTION 2. METHOD

SUBJECTS

Forty-eight drivers participated in this study. Twenty-four drivers were between the ages of 25 and 34. The remaining 24 drivers were at least 65 years old, with 12 between 65 and 69, and 12 age 70 or older. Half of the drivers in each age group were male, and half were female. The drivers were volunteers recruited through advertisements in the Iowa City and University of Iowa daily newspapers who met the following selection criteria:

- They had no licensing restrictions, other than wearing eyeglasses for vision correction during driving.
- They did not require special driving devices (the simulator is not equipped for such devices).
- They were medically screened to ensure good physical and mental condition.

Thirty-six drivers, 18 younger and 18 older, were assigned to the experimental groups. The remaining six younger and six older drivers were assigned to the control group.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator, located in the Center for Computer-Aided Design at the University of Iowa, Iowa City, is shown in figure 1.[8] The physical configuration consists of a domed enclosure mounted on a hexapod motion platform. The hexapod motion system employs 3.7-m- (60-inch-) stroke hydraulic actuators to induce six-degree-of-freedom motion cues to the driver. The motion system is capable of inducing correlated motion up to 5 Hz, vibration noise up to 8 Hz, and accelerations exceeding 1.0 *g*.

In this experiment, a Ford Taurus sedan was mounted on the motion platform, and the simulator was controlled by a computer complex that included a Harris Nighthawk 5800 and an Evans and Sutherland ESIG 2000 Computer Image Generator (CIG). The Nighthawk was controlled by the ICON operating system.[9] The Nighthawk was responsible for arbitrating subsystem scheduling and performing motion control, data-collection operations, instrumentation, control loading, and audio cue control. It also performed the multibody vehicle dynamics and complex scenario-control simulation.

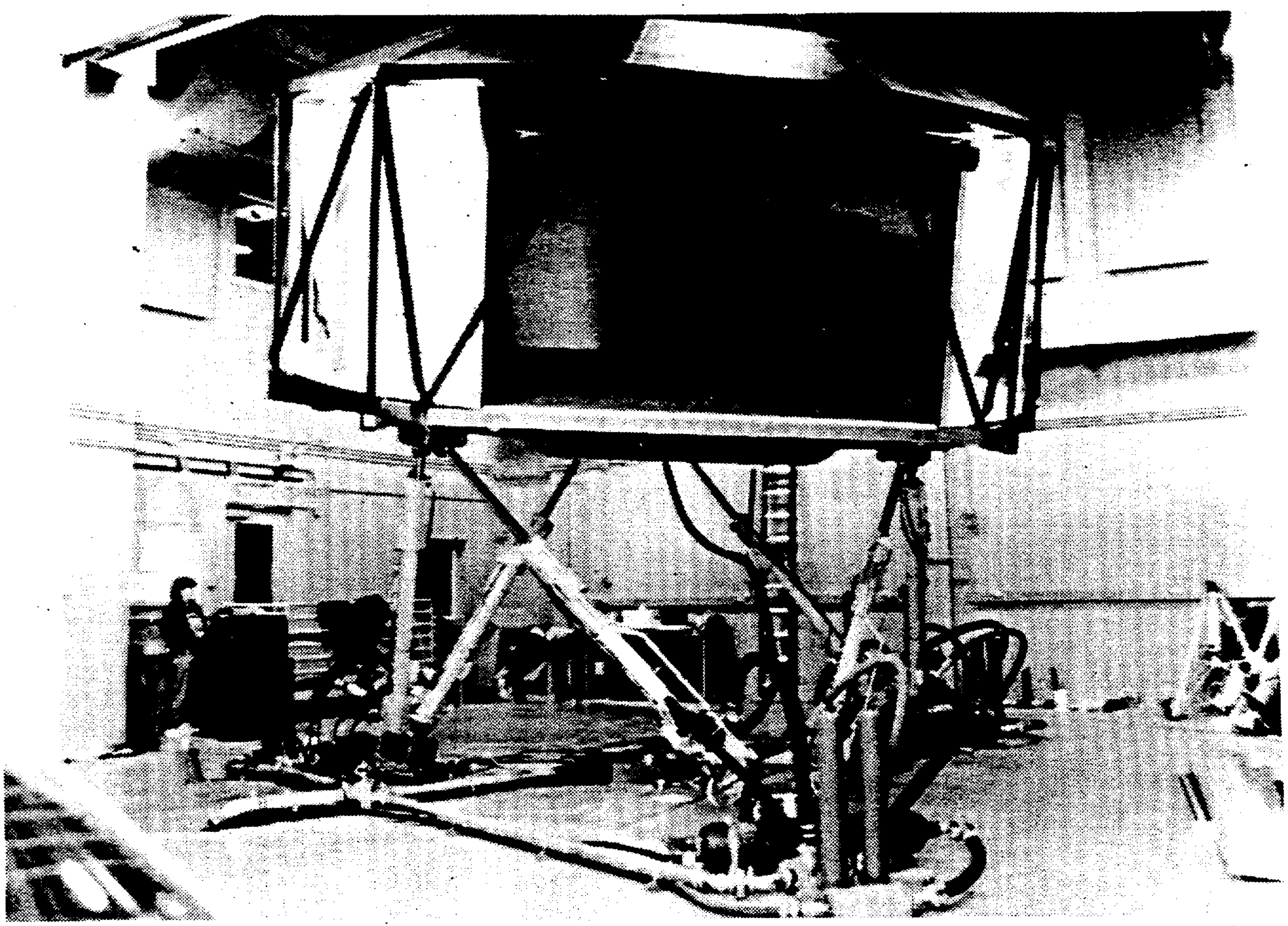

Figure 1. The Iowa Driving Simulator.

The inner walls of the dome act as a screen. For the current experiment, the correlated images generated by the CIG were projected onto two sections of these walls: one a 3.32-rad (190°) section in front of the simulator vehicle, the other a 1.13-rad (65°) section to its rear. The driver of the simulator vehicle viewed the images shown on the forward section through the windshield and side windows, and the images projected to the rear through an interior rear-view mirror, through a left side exterior driving mirror, or by turning around and looking through the back window.

DATA-COLLECTION PERIODS

Driving-performance data were obtained from 48 drivers, each of whom traveled on a simulated journey of approximately 1 h. The experience of the drivers in the experimental groups was considerably different from that of the drivers in the control group. For the 36 drivers who were in the experimental groups, the journey was divided into three sections: a pre-AHS, an AHS, and a post-AHS portion. The remaining 12 drivers, who were in the control group, retained control of the vehicle throughout the journey. Table 2 shows the timeline for the two groups.

The first 5 min of the journey were treated as practice for all 48 drivers—no driving-performance data were collected in this period. Then, at the beginning of the sixth minute of the trial, the first driving-performance data collection began: this was the early data-collection period. For the drivers in the experimental group, these pre-AHS driving-performance data were collected from the beginning of the sixth minute until the AHS issued a message requesting the driver to move into or stay in the center lane. Driving-performance data were collected from the drivers in the control group for the same time period.

Then, in the central portion of the trial, for the drivers in the experimental groups the simulator vehicle was in the automated lane under the control of the AHS for at least 35 min. For the drivers in the control group, the central portion of the trial lasted for 35 min, but they remained in control of their vehicles throughout this period.

Table 2. Trial timeline.

Length of Time	Experimental-Group Activity	Control-Group Activity
Trial start	Car on expressway entry ramp	Car on expressway entry ramp
9.5 min[a] **Early data-collection period**	Driver drives onto expressway, drives in right and center lanes	Driver drives onto expressway, drives in right and center lanes
About 1 min	AHS takes control in center lane and drives car into left lane; car is last in a string	Driver drives in right and center lanes
At least 35 min	Car under automated control	Driver drives in right and center lanes
About 1 min	AHS drives car into center lane and releases control to driver	Driver drives in right and center lanes
About 9 min **Late data-collection period**	Driver drives in center and right lanes	Driver drives in right and center lanes

[a] Minutes 0 through 5 were for driver practice; no data were analyzed for that time period.

In the final portion of the journey, the late data-collection period, driving-performance data were again collected. For the drivers in the experimental groups, these post-AHS driving-performance data were collected from the time that complete control of the simulator vehicle had been transferred from the AHS back to the driver. This transfer of control began approximately 10 min before the end of the trial and took approximately 60 s to complete. So, for the drivers in the experimental groups, the late data-collection period was approximately 9 min long. For the drivers in the control group, the second data-collection period began at the beginning of the 52nd minute and ended at the end of the 60th minute.

DRIVING SITUATION

The driving situation for the combined experiment can be described using the taxonomy of interactions between the driver and the AHS developed by Bloomfield et al.[(1)] Each driver drove in dry weather conditions, at midday, on a three-lane expressway. The route was 96.6 km (60 mi) long. A map of this route is presented in appendix 1. It contained 12 left curves and 8 right curves, all of which were 1.57-rad (90°) constant-radius curves. The radius of each curve was 762.5 m (2500 ft) and the superelevation was 0.04. The left lane was automated, the center and right lanes were unautomated, there was no transition lane, and there were no barriers between the automated and unautomated lanes. The lane widths were the current recommended minimum 3.7-m (12-ft) expressway width, and a standard road surface was used.

All the automated vehicles involved in the experiment were directly controlled by the AHS. When the driver's vehicle was under AHS control, the vehicle's steering wheel reflected the steering input from the AHS, the accelerator pedal reflected the throttle control by the AHS, and the brake pedal was disconnected.

The posted speed limit in the unautomated lanes was 88.6 km/h (55 mi/h). In the center and right lanes, the average velocity of the unautomated vehicles was 88.6 km/h (55 mi/h). The traffic density in the unautomated lanes was 12.42 v/km/ln (20 v/mi/ln). This traffic density level is close to the upper boundary of the Transportation Research Board Level of Service B (LOS B).[10] At this density, traffic flow is stable but the presence of other vehicles is noticeable and there is a slight decline in the freedom to maneuver; the mean headway time for vehicles in the unautomated lanes was 3.3 s. [Note: Mean headway time is the difference in arrival time of two consecutive vehicles at a particular observation point on the highway. It includes both the length of the first vehicle and the gap between it and the following vehicle.] The distribution of the velocities of the unautomated vehicles was normal, while a Pearson Type III distribution was used to generate the time headways. The method used to generate vehicles in this experiment is described in detail by Bloomfield et al.[1] The parameters used in the equations, defining both the normal distribution of velocities and the Pearson Type III distribution were derived using the procedure described by May and using the data provided by May.[11,12]

For the drivers who were in the experimental groups, in the first portion of the trial the driver controlled the simulator vehicle, driving for at least 15 min in the right and center lanes of the expressway. After this, control of the vehicle was transferred to the AHS. Then, in the second portion of the trial, which lasted at least 35 min, the driver's vehicle was under automated control, traveling most of that time in the AHS (left) lane. During this portion of the trial, each driver was able to use a laptop computer that provided various types of information, including the current location of the vehicle, the traffic conditions ahead, the estimated travel time to the destination, and the next exit and the distance to it (more details of this aspect of the combined experiment are given by Levitan and Bloomfield[7]). Then, in the third section of the trial, the drivers in the experimental groups again controlled the vehicle, this time driving for approximately 10 min in the center and right lanes.

For the drivers who were in the control group, there was no way to differentiate among the three portions of the trial. As far as these drivers were concerned, they simply drove in the expressway for 1 h. However, driving-performance data were obtained from these drivers early and late in the trial, at times that corresponded to the times at which data were collected from the drivers in the experimental groups, i.e., the first set of data were collected from the control-group drivers between the beginning of the 6th minute and the end of the 15th minute of the trial, while the second set of data were collected between the beginning of the 51st minute and the end of the 60th minute of the trial.

A strip map that indicated all the exits that the driver could encounter by name (e.g., County Road F) and number (e.g., Exit 24) was placed on the front passenger's seat of the car for only the experimental group. The distances between exits were not shown on the map. No instructions were given regarding the map, which is shown in appendix 1. The driver was free to use it whenever he/she wished.

EXPERIMENTAL DESIGN

Four independent variables were investigated. The first was a within-subjects variable that involved comparing the driving-performance data that were obtained in two data-collection periods: one that occurred early in the trial, the other that occurred late in the trial. The second independent variable, the age of the driver, was a between-subjects variable that could have affected the driver's performance in both data-collection periods. The remaining two variables were also between-subjects variables. But, unlike the age of the driver, they could only affect driving performance in the post-AHS segment of the trial. The reason for this was that the two variables, the intra-string gap and the method of transferring control from the AHS back to the driver, were not experienced by the driver until after he/she had traveled in the automated lane. Because of this, it was not expected that the main effect of either of these variables would be statistically significant. If either the intra-string gap or the control transfer method (described in the eponymous section below) had an effect, it was expected to be in an interaction with the pre- and post-AHS variable.

Data-collection period

Driving-performance data were collected in two data-collection periods: the first was a 9.5-min period that, for all drivers, began at the beginning of the sixth minute of the trial; the second was a 9.0-min period that, for the drivers in the experimental groups, began as soon as they regained control after traveling in the automated lane, and ended 9.0 min later, and, for the drivers in the control group, began at the beginning of the 52nd minute of the trial and finished at the end of the 60th minute.

Age of the Driver

The 60 drivers who took part in the current experiment were from two age groups. The first group consisted of drivers between 25 and 34 years of age, while the drivers in the second group were age 65 or older. There were 24 drivers in each group. To ensure that they represented the populations from which they were drawn, both groups were balanced for gender: half of the drivers in each group were male and half were female. In addition, to ensure that the ages of the older drivers did not cluster around the lower limit for the group, 12 of them were between 65 and 69 years of age and 12 were age 70 or older.

Intra-String Gap

After driving in the right and center lanes for approximately 15 min, the driver transferred control of the simulator vehicle to the AHS. The transfer of control occurred while the vehicle was in the center lane. The AHS moved the vehicle into the automated lane, increased its velocity, and positioned it at the end of the string of vehicles immediately ahead. After the driver's car had been under the control of the AHS for approximately 35 min, control was transferred back to the driver. Before relinquishing control, the AHS detached the simulator vehicle from the string of vehicles, by decreasing its velocity, and moved it into the center lane. Except during these two transitions, the driver's vehicle was in the automated lane, as the last vehicle in a string, throughout the period of time it was controlled by the AHS. The distance between the front bumper of the driver's car and the back bumper of the vehicle ahead took one of two values: for half of the drivers, this distance, the intra-string gap, was 0.0625 s (this was the smallest intra-string gap that was used in the stage I experiments); for the other half of the drivers, the intra-string gap was, at 0.0344 s, even shorter. Since the designated AHS velocity was 104.7 km/h (65 mi/h), the distance between the driver's car and the vehicle ahead was 1.8 m

(6.0 ft) when the intra-string gap was 0.0625 s, and 1.0 m (3.3 ft) when the intra-string gap was 0.0344 s.

Control-Transfer Method

After traveling under automated control for at least 35 min, control of the simulator vehicle was transferred back to the driver. While the vehicle was still in the automated lane, the AHS notified the driver that the vehicle would leave the automated lane in 30 s. After 30 s had passed and a suitable gap occurred between two unautomated vehicles in the center lane, the AHS reduced the speed of the vehicle to 88.6 km/h (55 mi/h), detached it from the string of vehicles, and moved the vehicle into the center lane. Once the vehicle was in the center lane, the AHS informed the driver how to take control of the vehicle in one of three ways:

- Speed first. With this method, the AHS first issued a message instructing the driver to take control of the speed of the vehicle by pressing down the brake or accelerator. Then, when the driver had control of the speed, the AHS issued a second message, which instructed the driver to take control of the steering by taking hold of the steering wheel. As soon as the driver was holding the steering wheel, the AHS issued a third message stating that the driver now had full control of the vehicle. If the driver failed to take control of either function within 15 s after the message was issued, the message was repeated. If the driver failed to take control of the function within 15 s of the third instance of the message, the simulation was stopped and the experiment ended.

- Steering first. With this method, the AHS first issued a message instructing the driver to take control of the steering by taking hold of the steering wheel. As soon as the driver was holding the steering wheel, the AHS issued a second message that instructed the driver to take control of the speed by pressing down the brake or accelerator. When the driver pressed the brake or accelerator, the AHS issued a third message stating that the driver now had full control of the vehicle. If the driver failed to take control of either function within 15 s after the message was issued, the message was repeated. If the driver failed to take control of the function within 15 s of the third instance of the message, the simulation was stopped and the experiment ended at that point.

- Speed and steering simultaneously. With this method, the AHS issued a message instructing the driver to take full control of the vehicle by holding the steering wheel and then pressing down the brake or accelerator. As soon as the driver had taken both of these actions, the AHS issued another message, which stated that the driver now had full control of the vehicle. If the driver failed to take control within 15 s after the message was issued, the message was repeated. Then, if the driver failed to take control within 15 s of the third instance of message, the simulation was stopped and the experiment ended at that point.

With all three methods, the system provided the opportunity for the driver to take control, but control was not released until the driver actively took control. The simulation was not stopped for any subject for failing to take control of the car.

Assignment of Drivers and Treatment of the Control Group

To determine the effects of 4 independent variables using 48 drivers, it was necessary to conduct 2 separate sets of analyses. Both sets used the same data, each analyzing the effects of three of the variables while collapsing the data across the fourth. Two of the variables were common to both sets of analyses. The data obtained in the early and late data-collection periods were compared and the effects of the age of the driver were explored by both sets.

In addition, the first set of analyses investigated the effects of varying the intra-string gap (collapsing the data across the methods of transferring control). If any analysis in this first set were to indicate that there was a statistically significant intra-string gap effect, this could be for one of two reasons: because there was, in fact, a difference in the performance of the drivers in the two intra-string-gap conditions, or because there was a difference in performance between the drivers who were in the control group and the experimental-group drivers (who experienced the different intra-string gaps).

The second set of analyses investigated the effect of varying the method of transferring control back to the driver (collapsing the data across the intra-string gaps). If any analysis in this second set were to indicate that there was a statistically significant effect of the method of transferring control, this, too, could be for one of two reasons: because there were, in fact, differences in the performance of the drivers in the three control-transfer-method conditions, or because there was a difference in performance between the drivers who were in the control group and those who were in the experimental group (and had experienced the different transfer methods).

For the analysis investigating the effect of varying the intra-string gap, the 48 drivers who took part in the experiment were divided into the 6 groups shown in table 3. Nine drivers were assigned to each of the four combinations of driver's age and intra-string gap, while there were six older and six younger drivers who were controls.

Table 3. Number of drivers for each combination of intra-string gap and the age of the driver.

	Driver Age	
Intra-String Gap	25 Through 34	65 and Older
0.0344 s	9	9
0.0625 s	9	9
Control Group	6	6

For the second analysis, the 48 drivers were divided into the 8 groups shown in table 4. There were six drivers for each combination of driver's age and method of transferring control, as well as the six older and six younger drivers who were controls.

Table 4. Number of drivers in each combination of method of transfer and the age of the driver.

	Driver Age	
Control Transfer Method	25 Through 34	65 and Older
Speed First	6	6
Steering First	6	6
Speed and Steering Together	6	6
Control Group	6	6

The combination of intra-string gap and method of transferring control experienced by each of the 48 drivers is shown in appendix 2.

EXPERIMENTAL PROCEDURE

The combined experiment was divided into two sessions. In the first session, the drivers watched an introductory videotape, drove for one experimental trial in the Iowa Driving Simulator, and filled out a questionnaire. In the second session of the experiment, the driver's visual capabilities were assessed.

Introduction, Training, and Practice Procedure

Before the start of the experiment, each driver watched a videotape containing introductory material describing this research program and the AHS, and providing some interactive practice with the AHS interface and protocol. The driver was told that the experiment involved first driving in the simulator and then completing several vision tests and a questionnaire. The driver was informed that this experiment is part of an ongoing FHWA program that is exploring ways of designing an AHS, determining how it might work, and how well drivers would handle their vehicles in such a system. It was made clear that the experiment was a test of the AHS, not a test of the driver. The video then gave explanations of the subtasks for the experiment and provided details to the drivers on how to:

- Transfer control of the vehicle to the AHS on entering the automated lane.
- Obtain information about their journey using the laptop computer mounted in the vehicle.
- Regain control back from the AHS on leaving the automated lane.

Four different versions of this training video were prepared: one version for each of the three different methods of transferring control from the AHS back to the driver at the end of the automated section of the drive, and one version for the control-group drivers who did not experience automated travel. The narrations of these four versions of the training videos are presented in appendix 3.

The instructional section of the three videos prepared for the drivers who were to travel in the automated lane lasted 10 min. The fourth version of the video, produced for the drivers in the control group, required less detail and was 3 min in length. When the videos were presented to the drivers, who were seated in a driving buck, the volume was adjusted so that the AHS messages were precisely as loud in the video as they would be in the simulator vehicle. Before the training video was presented, the drivers were told to pay particular attention to the auditory messages, as they would be exactly what would be heard in the vehicle. Then, after the training video was complete, the driver was asked:

> "Did you have any difficulty hearing any of those messages?"

This procedure was adopted to ensure that each driver would be able to hear the messages when they were presented during the experimental trial.

After the instructional section of the videos, each version continued with a series of practice segments. The first of these segments contained subtask practices that dealt with transferring control to the AHS, using the laptop computer to obtain information about the drive, and transferring control back from the AHS to the driver. An example of a subtask would be pressing the brake pedal or accelerator pedal in response to a request from the AHS. There were three practice segments for each of these subtasks. If the driver responded correctly on the first two segments, the third was omitted. If the driver did not respond correctly twice in a row for a particular subtask, the three segments were repeated until the driver was able to accomplish this. Following the subtask practices, the videos concluded with three more segments that covered the whole task for the driver. As before, if the driver responded correctly on the first two trials, the third was omitted, and if more than three trials were required, the segments were repeated.

Pre-Experimental Simulator Procedure

The driver was taken to the Iowa Driving Simulator and seated in the driver's seat of the simulator vehicle. The driver was asked to put on the seat belt and adjust the seat and mirrors, and then was given instructions on how to use the simulator emergency button. The driver was made aware that the headlights of the vehicle were already switched on, and that the air conditioner, dome lights, turn signal, and radio were operational. The driver was told that, if for any reason he/she wanted to stop at any time during the drive, to simply say so and the operator would stop the simulation.

Experimental Procedure and Instructions I

Each driver drove the simulator vehicle for one extended trial that lasted approximately 1 h. At the beginning of the trial, the vehicle was parked on a freeway entrance ramp. The driver was instructed to drive into the right lane of traffic on the three-lane expressway. The driver then drove in the right lane and the center lanes for at least 15 min. The density of the traffic in these two lanes was 12.42 v/km/ln (20 v/mi/ln).

For the sake of completeness, the instructions description indicates places where noncompliance would have led to termination of the experiment for that subject. No subject was terminated for failing to comply with instructions.

The driver was told that the left lane was reserved for automated vehicles, and that if he/she drove into it, the following auditory warning would be heard:

> "You've entered the left lane. You're not authorized to be in the left lane. Return to the center lane immediately."

At 14.5 min after the start of the trial, in order to prepare for entry into the AHS, the driver received one of two auditory messages: one was given if the driver's vehicle was in the right lane, the other if it was in the center lane. If the driver was in the right lane, the message was as follows:

> "Please move to the center lane and, when you get there, wait for further instructions."

[It is to be noted that a tone preceded each presentation by the AHS of an auditory verbal message, and whenever an auditory message was presented by the AHS, the car's radio speaker was silenced during the entire time the message was being presented.]

Then, as soon as the driver moved to the center lane, the following message was presented:

> "Please remain in the center lane and wait for further instructions."

If the driver did not comply with this message within 10 s, it was repeated; if the driver did not comply with the message after three presentations, the following message was presented and the experiment ended:

> "Please pull over to the right shoulder and stop."

If the driver was already in the center lane 14.5 min after the start of the trial, the AHS issued the following message:

> "Please remain in the center lane and wait for further instructions."

If the driver did not comply, and left the center lane, the following message was presented:

> "Please move to the center lane and, when you get there, wait for further instructions."

If the driver did not comply with this message within 10 s, it was repeated; if the driver did not comply with the message after three presentations, the following message was presented and the experiment ended:

> "Please pull over to the right shoulder and stop."

When the driver's vehicle was in the center lane at least 15 min after the start of the trial, the AHS presented the following message:

> "To engage the automated system, push the *On* button now."

If the driver complied, by pressing the *On* button on the steering wheel, the following message was presented in an auditory manner:

> "Welcome to the Automated Highway System. Your vehicle is now controlled by the automated system. You will enter the automated lane in a moment."

If the driver did not press the *On* button, the message was repeated twice at 10-s intervals. If the driver still failed to comply 5 s after the second repetition, the driver was instructed by the AHS to pull over to the right shoulder and stop, and the experiment ended.

Throughout the preautomated portion of the trial, the simulator vehicle remained under the control of the driver.

AHS Experience

As soon as the driver pressed the *On* button, the AHS took full control of the simulator vehicle and drove it into the automated lane. It entered the lane between two strings of automated vehicles. Once in there, the AHS increased the velocity of the driver's car until it caught up to the string ahead. It then joined that string as the last vehicle.

A laptop computer located to the driver's right was automatically activated when the vehicle entered the automated lane. The driver, who was trained how to use the computer and what information was available on it, was able to use this computer to obtain various types of information (i.e., current location, traffic conditions ahead, the estimated travel time to the destination, and the next exit and distance to it) while the vehicle was in the automated lane (see the report by Levitan and Bloomfield for more details of this aspect of the combined experiment).(7) The simulator vehicle traveled under automated control for at least 35 min. It remained the last vehicle in the string throughout this period of time. The computer was automatically turned off at the end of the period of automated travel.

Experimental Procedure and Instructions II

For the sake of completeness, the instructions description indicates places where noncompliance would have led to termination of the experiment for that subject. No subject was terminated for failing to comply with instructions.

After traveling under the automated control for at least 35 min, control of the simulator vehicle was transferred back to the driver. While the vehicle was still in the automated lane, the AHS used the following message to notify the driver that the vehicle would leave the automated lane:

> "You will leave the automated lane in 30 seconds. Once in the center lane, you will be asked to resume control of your vehicle."

Then, when a suitable gap occurred between two unautomated vehicles in the center lane, the AHS reduced the speed of the vehicle from 104.7 km/h (65 mi/h) to 88.6 km/h (55 mi/h), detached it from the string of vehicles, and moved the vehicle out of the automated lane. Once the vehicle was in the center lane, the AHS informed the driver how to take control of the vehicle in one of three ways. The first method was to regain control of the speed of the vehicle first, then the steering. Twelve drivers regained control of the vehicle in this way. The transfer of control from the AHS to the these drivers began when they heard the following message:

> "To regain control of the speed, press the accelerator or brake pedal."

When the driver had pressed the brake or accelerator and regained control of the speed, the AHS issued a second message:

> "You now control the speed. To regain control of the steering, put your hands on the steering wheel."

As soon as the driver was holding the steering wheel, the AHS issued a third message stating:

> "You now have complete control of your vehicle."

If the driver failed to take control of either function within 5 s of the message being issued, the message was repeated. If the driver failed to take control of the function within 5 s of the third instance of either message, the simulation was stopped and the experiment ended at that point.

The second method was to regain control of the steering first, then the speed. There were also 12 drivers who regained control of the vehicle this way. The transfer of control from the AHS to these drivers began when they heard the following message:

> "To regain control of the steering, put your hands on the steering wheel."

When the driver had put his/her hands on the steering wheel, and regained control of the steering, the AHS issued a second message:

> "You now control the steering. To regain control of the speed, press the accelerator or brake pedal."

As soon as the driver had taken control of the speed as well as the steering, the AHS issued a third message stating:

> "You now have complete control of your vehicle."

If the driver failed to take control of either function within 5 s of the message being issued, the message was repeated. If the driver failed to take control of the function within 5 s of the third instance of either message, the simulation was stopped and the experiment ended at that point.

The third method was to regain control of the speed and steering simultaneously. As with the other 2 control transfer methods, 12 drivers regained control of the vehicle this way. The transfer of control from the AHS to these drivers began when they heard the following message:

> "To regain control of the vehicle, put your hands on the steering wheel and press the accelerator or brake pedal."

As soon as the driver had complied with both requirements—holding the steering wheel while pressing either the accelerator or the brake pedal—the AHS issued this message:

> "You now have complete control of your vehicle."

If the driver failed to take control within 5 s of the message being issued, the message was repeated. Then, if the driver failed to take control within 5 s of the third instance of the message, the simulation was stopped and the experiment ended at that point.

After regaining control of the vehicle in one of these three ways, the driver continued driving in the unautomated lanes for approximately 10 min, until the end of the drive.

Control Group

Each driver in the control group was informed that there was an automated lane, that he/she was not supposed to drive in it, and that if he/she did try to move into that lane a warning message would be issued. The driver was also told that the speed limit in these lanes was 55 mi/h.

Post-Experimental Procedure

After completing the trial, the driver returned to the subject preparation room. Once there, the driver was debriefed and asked to complete a questionnaire that contained questions dealing with the driving simulator, his/her drive in the simulator vehicle, the laptop information, and the AHS. There were four different versions of the questionnaire, one for each method of control transfer and one for control subjects. Copies of these questionnaires are presented in appendix 4. The first part of the experiment ended here.

The visual capabilities of the driver were assessed in the second part of the experiment. This was done simply to see whether any subject had an anomaly that would warrant taking a closer look at his/her data. Most of the drivers who participated in the experiment took a 5-min break before the second part of the experiment. A few drivers were unable to complete the visual testing on the same day, and they returned on a later date to complete it.

Vision testing was divided into two sections. In the first section, a standard set of vision tests was administered: far foveal acuity, near foveal acuity, stereo depth perception, color deficiencies, lateral misalignment, and vertical misalignment. In the second section, the spatial localization perimeter developed by Wall was used to determine the subject's reaction time and accuracy when detecting both static and dynamic peripheral stimuli.[13]